UNIAXIAL COMPRESSION TESTS FOR POSSIBLE DAMAGE TO SURROUNDING ROCKS DURING CANISTER RETRIEVAL TEST AT ÄSPÖ IN SWEDEN

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Abstract：The canister retrieval test(CRT) was a test of a full-scale copy of a repository carried out from October 2000 to November 2005 at Äspö underground laboratory. Due to the excavation of the deposition hole DD0092G01 and the heating in the canister within the hole，there was a concern for the CRT rock volume if the changed stress around the deposition hole could lead to microfracturing in or other damage to the surrounding rocks. For this purpose，uniaxial compression testing has been performed on 12 core samples taken from different parts of sub-horizontal core boreholes drilled at three depths in DD0092G01 in the directions parallel and perpendicular to that of the major principal stress. The uniaxial compression strength(UCS) and Young′s modulus，the crack initiation stress(σ_{ci})，crack damage stress(σ_{cd})，and the maximum crack volumetric strain(ε_{vcmax}) and maximum total volumetric strain(ε_{vmax}) have been compiled and analyzed. Comparisons were made according to the sampled direction to the major principal stress and the distance to deposition hole wall. It has been inferred from the slightly higher values of maximum crack volumetric strain that some damages，but only to a small extent and in the form of micro-fracturing，occurred in the rock near the deposition hole wall in the direction perpendicular to the major principal stress. There is no evidence of any damage from other mechanical properties.

Key words：high-level radioactive waste；canister retrieval test(CRT)；uniaxial compression strength(UCS) testing；maximum crack volumetric strain；damage

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用单轴抗压强度试验分析瑞典 Äspö 废物罐回取试验中的岩石损伤

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摘要：废物回取试验是一个在瑞典 Äspö 地下实验室完成的，历时近 5 a，为全尺寸处置库模拟加热试验。试验在

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一个直径ϕ1.75 m、深度 8.5 m 的钻孔中进行。开挖和加热后周边岩石中的温度升高、应力改变，因此，试验中岩石中可能产生的损伤是工程设计中关心的课题之一。为此，试验结束后，在试验孔 3 个不同深度处沿垂直和平行于最大主应力方向施打 6 个深度约 1.5 m 的近水平取样孔，并采集了 12 组岩样。对这 12 组岩样用 MTS 815 岩石力学试验系统进行了单轴抗压强度试验。从单轴抗压强度、裂隙起始应力、裂隙损伤应力、最大裂隙体积应变和最大总体变进行了对比和分析，试验结果分析表明：从最大裂隙体积应变分析，在垂直于最大主应力方向的处置孔孔壁的岩石上可能存在一些轻微的微破裂为特征的损伤。从宏观力学特性来说，岩石没有任何可测的损伤。
关键词：高放废物；废物罐回取试验；单轴抗压强度试验；最大裂隙体积应变；损伤

1　INTRODUCTION

Retrievability is one of the requirements for high-level radioactive waste disposal in Sweden. To test the methods for canister retrieval from a saturated buffer，a canister retrieval test(CRT) was carried out at Äspö Hard Rock Underground Laboratory[1] in Sweden from October 2000 to November 2005. A deposition hole(DD0092G01) with the diameter of ϕ1.75 m and depth of 8.5 m was drilled and the stress in the surrounding rock was changed. During the test，the canister in the deposition hole was heated with a maximum heat power of 2 600 W. Therefore，the surrounding rock of the hole was heated and the temperature was elevated，which further led to stress increase in the surrounding rock volume. Therefore，there was a concern for CRT rock volume if the increased stress around the deposition hole could lead to microfracturing in or other damage to the surrounding rocks and one would like to know how to estimate and evaluate its occurrence.

Thermomechanical damage in rocks can be investigated experimentally or numerically[2－4]. In this paper，experimental methods will be adopted to investigate if the increased stress around the deposition hole has led to the micro-fracturing in or other damage to the surrounding rock. Uniaxial compression tests were conducted on core samples taken from different parts of the sub-horizontal core boreholes drilled at three depths in DD0092G01 both parallel and perpendicular to the direction of the major principal stress. Comparisons of testing results were made among samples taken from different directions to the major principal stress and different distances to the deposition hole wall. The micro-fracturing or damage was mainly examined and identified by crack-related parameters with the focus on the maximum crack volumetric strain during the elastic stage of uniaxial compression tests.

2　GEOLOGICAL BACKGROUND

The tunnel for the canister retrieval test is a part of the TASD-tunnel and situated approximately on the 420 m-depth of the tunnel system at the Äspö Hard Rock Laboratory[5，6]. To accommodate the canister，a large deposition hole(DD0092G01)，with the diameter of ϕ1.75 m，was drilled to the approximate depth of 8.5 m by specially made vertically drilling Robbins TBM in 1999.

Four rock types are presented in the canister retrieval test tunnel. The rock types are Äspö diorite(31%)，greenstone(56%)，fine-grained granite (11%)，and pegmatite(2%).

The same four types of rocks have been distinguished in DD0092G01. Äspö diorite is mainly of the feldspar megacryst bearing type and it is partly slightly schistose. It constitutes about 30% of the hole-surfaces(wall and bottom) and appears mainly in the lower half of the hole. Greenstone is medium-grained and constitutes 38% of the hole and mainly occurs at upper half of the hole. Fine-grained granite constitutes 25% of the hole-surfaces，while pegmatite constitutes only about 5% of the surfaces.

The geostress in Äspö is anisotropic. The maximum and minor horizontally principal stresses are estimated to be 30 and 10 MPa and in the direction NE 310° and N40° respectively.

3　EXPERIMENT DETAILS

The experimental setup is shown in Fig.1. The deposition hole(DD0092G01) for CRT has a diameter of 1.75 m and depth of 8.5 m. In CRT，the test installation mainly consisted of a full-scale deposition hole[7, 8] as previously described；a copper canister equipped with electrical heaters，and bentonite blocks(cylindrical and ring-shaped). A 0.15 m height concrete foundation was built at the bottom of the deposition hole. The copper canister was of full scale and obtained from SKB′s encapsulation project. It had heaters inside and was placed inside the hole. The canister was 1 050 mm in diameter，4.83 m in height and had the weight of 21.4 tons. The bentonite buffer was installed in the form of blocks and rings，with an initial density of 1 710 and 1 790 kg/m^3 respectively；and initial water content is 17%. The blocks have a diameter of 1.65 m and a height of 0.5 m. When the stack of blocks was 6 m high，the canister equipped with electrical heaters was lowered down in the centre of the hole；and the cables to the heaters and instruments were connected. Additional blocks were emplaced until the hole was filled to a distance of one meter from the tunnel floor. The top of the hole was sealed with a retaining plug made of concrete and a steel plate. The plug was secured against heave that was caused by the swelling clay with nine cables anchored in the rock. Strips of matting were attached to the rock wall. Water was supplied artificially for saturation around the bentonite blocks. The cables from all instrumentation in the bentonite，deposition hole wall，canister，heaters in the canister，and the pipes for water supply，were placed in four types of slots cut in the hole wall(100－200 mm in width，40－60 mm in depth and 2 200 or 3 100 mm in length). The gap between the bentonite rings(or bentonite blocks) and the rock surface was filled with bentonite pellets and water.

The heating of the CRT canister started with an initially applied constant power of 700 W on October 27，2000. It was then raised to 1 700 W on November 13(the 17th day) and further to 2 600 W on February

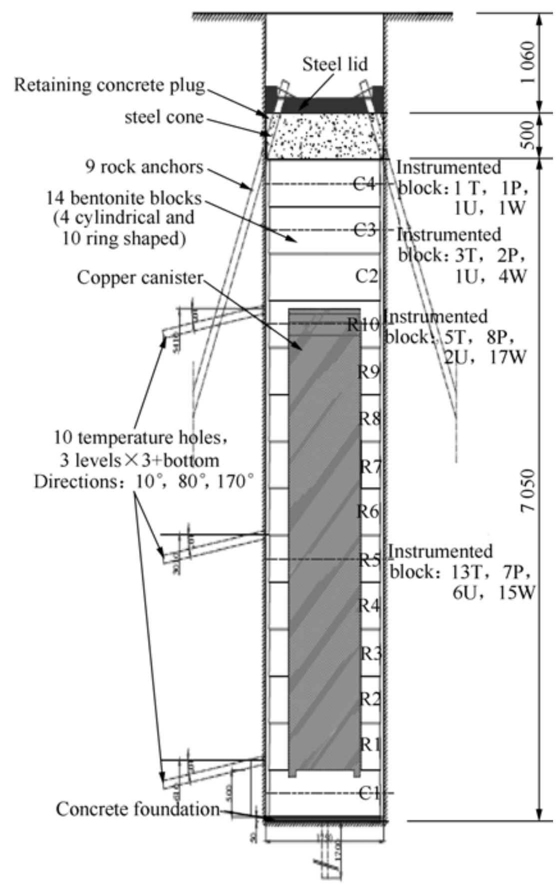

Fig.1　The CRT sketch of experimental setup(unit：mm)

13，2001(the 103rd day). It was reduced to 2 100 W on the 683rd day(September 10，2002) and to 1 600 W on the 1 135th day(December 4，2003) and further to about 1 150 W on March 10，2005(the 1 596th day). No power was generated during one day between November 5 and 6，2001(the 375th day) and one week between March 4 and 11，2002(from 495th to 502nd days). On October 11，2005(the 1 811th day)，the power was switched off in order to prepare for the dismantling，excavation and retrieval of the canister，which were carried out at the beginning of 2006.

The maximum value of measured temperature in the rock was about 65 ℃. A careful observation of the CRT deposition hole surface after the completed experiment shows that no obvious change and visible damage could be found.

4　UCS TESTING AND RESLUTS ANALYSES

4.1　Samples description

After the CRT，6 sub-horizontal core boreholes[9] (numbered KD0092G17－G22) were drilled about 1.5 m into the rock from the rock wall of the CRT deposition hole(DD0092G01) at three depths，3.4，6.0 and 7.9 m respectively，counting from the tunnel floor. The holes had been drilled parallel(KD0092G20，G21，G22) and perpendicular(KD0092G17，G18，G19) to the directions of the maximum principal stress to make the maximum and minimum loaded parts of the rock sampled. In total，12 core samples were collected. The location details and description of these samples are given in Table 1 and Fig.2.

The samples from the upper part of the deposition hole wall(samples from KD0092G17，G18，G20，G21) are greenstone，whereas the samples from the lower part are Äspö diorite. Some foliations were found in samples taken from KD0092G20 and G21 and veins or inclusion of granite were seen in some samples. As a whole，the samples collected from different directions and different parts of the core boreholes show no obvious geological difference.

4.2 Experimental method

The uniaxial compression tests were executed with the Rock Mechanics Testing System(MTS 815) at the Laboratory of Rock Engineering，Helsinki University of Technology[10]. The test methodology follows the International Society of Rock Mechanics (ISRM) suggested method[11].

The test specimens were water-saturated according to the standard[12]. In all uniaxial compression tests，the acoustic emission was monitored with an independent system，not interfering with the uniaxial compression test，to estimate crack initiation and crack damage stress. Acoustic emission measurement followed methodology developed for Posiva site investigations[13].

4.3 Data analysis and interpretation

Axial strain and radial strain are plotted against axial stress(Fig.3). Young′s modulus and Poisson′s ratio are determined at axial stress level equal to 50% of the uniaxial compressive strength of the specimen[10].

During the elastic stage of a uniaxial compression test，assuming the Young′s modulus and Poisson′s ratio be constant，the total volumetric strain ε_{v}，the elastic volumetric strain $\varepsilon_{\mathrm{ve}}$ and the crack volumetric strain $\varepsilon_{\mathrm{vc}}$ can be calculated from the following expressions[12，13]:

Table 1 Samples′ locations and rock types

Borehole number	Sample number	Direction	Depth/m	Distance/m	Rock description
KD0092G17	G17－113－1	N40°E (perpendicular to σ_1)	3.4	0.03－0.18	Greenstone，mid-grained，with inclusion of granite
	G17－113－2			1.55－1.70	Greenstone，homogenous
KD0092G18	G18－113－1		6.0	0.03－0.18	Greenstone，mid-coarse grained，with some inclusion of granite
	G18－113－2			1.40－1.55	Greenstone，homogenous
KD0092G19	G19－113－1		7.9	0.04－0.19	Äspö diorite，with veins of fine-grained granite
	G19－113－2			1.49－1.64	Äspö diorite
KD0092G20	G20－113－1	N310°E (parallel to σ_1)	3.4	0.06－0.21	Greenstone，with veins of fine-grained granite，slightly foliated
	G20－113－2			1.55－1.70	Greenstone，with inclusion of granite，slightly foliated
KD0092G21	G21－113－1		6.0	0.07－0.22	Greenstone，mid-coarse grained，with inclusion of granite and foliation
	G21－113－2			1.60－1.75	Greenstone with foliation
KD0092G22	G22－113－1		7.9	0.06－0.21	Äspö diorite
	G22－113－2			1.25－1.40	Äspö diorite

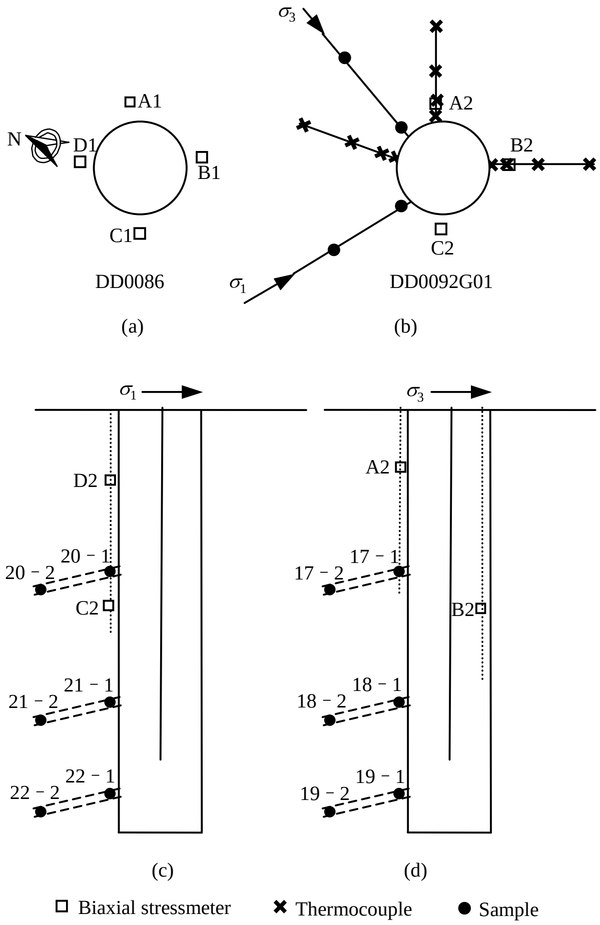

Fig.2　Schematic diagrams of the samples locations

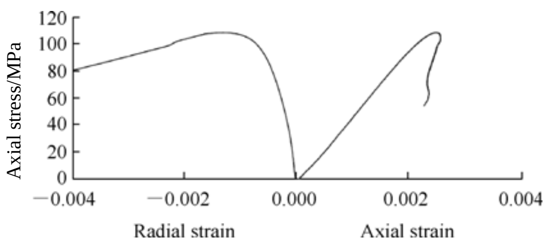

Fig.3　Axial strain and radial strain versus axial stress(G17－113－2)

$$\varepsilon_{\mathrm{v}} = \varepsilon_{\mathrm{a}} + 2\varepsilon_{\mathrm{r}} \tag{1}$$

$$\varepsilon_{\mathrm{ve}} = \sigma(1-2\nu)/E \tag{2}$$

$$\varepsilon_{\mathrm{vc}} = \varepsilon_{\mathrm{v}} - \varepsilon_{\mathrm{ve}} \tag{3}$$

where ε_{a}, ε_{r} are axial and radial strain respectively; and E, ν are Young′s modulus and Poisson′s ratio respectively.

Therefore, the total and crack volumetric strains (ε_{v} and $\varepsilon_{\mathrm{vc}}$) can be plotted against axial stress (Fig.4). Crack damage stress(σ_{cd}) is determined from the peak of the curve of total volumetric strain versus axial stress; and the crack initiation stress(σ_{ci}) is identified from the reversal point of the curve of

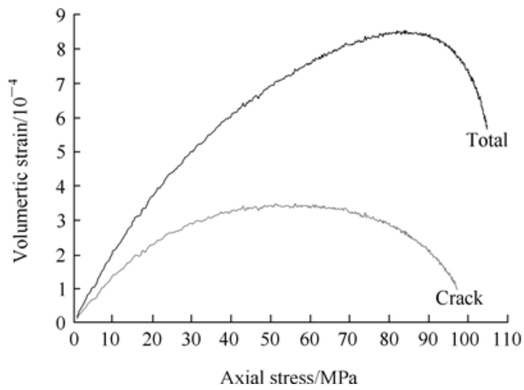

Fig.4　Volumetric strains versus axial stress(G17－113－2)

crack volumetric strain versus axial stress. The volumetric strains[9] corresponding to crack initiation stress(σ_{ci}) and crack damage stress(σ_{cd}) are called maximum crack volumetric strain($\varepsilon_{\mathrm{vcmax}}$) and maximum volumetric strain($\varepsilon_{\mathrm{vmax}}$) respectively.

The results of the acoustic emission measurements are presented as cumulative number of acoustic emission(AE) events versus axial stress(Fig.5)[13, 14]. In an ideal AE result, it is possible to separate the emission caused by load application, the elastic region, the initiation of microcracking, the onset of stable microcracking, and the beginning of unstable microcracking. Primarily, the initiation of micro-cracking is interpreted as the crack initiation stress (σ_{ci}); but, if the microcracking starts irregularly, being minor, then the onset of stable microcracking is used instead. The beginning of unstable microcracking, where the cumulative count-axial stress relation changes from linear to exponential, is defined as the crack damage stress(σ_{cd}).

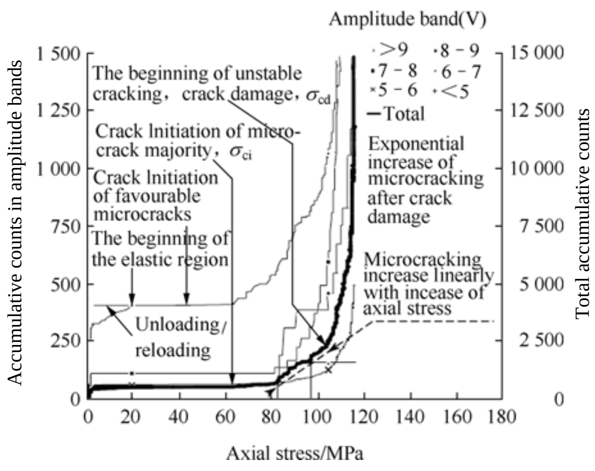

Fig.5　Interpretation of stress states from AE results[13, 14]

4.4 Experimental results and comparison

Tables 2，3 present some of the experimental and statistical results from uniaxial compression tests.

Table 2　Rock mechanical properties measured by UCS test

Sample number	Sample′s location direction(depth-distance)	*UCS* /MPa	Young′s modulus /GPa	Poisson′s ratio
G17－113－1	Perpendicular (3.4 m－top)	123.2	56.3	0.34
G17－113－2	Perpendicular (3.4 m－end)	108.5	50.8	0.32
G18－113－1	Perpendicular (6.0 m－top)	146.0	61.7	0.34
G18－113－2	Perpendicular (6.0 m－end)	115.2	53.5	0.35
G19－113－1	Perpendicular 7.9 m－top	170.1	65.6	0.31
G19－113－2	Perpendicular (7.9 m－end)	149.6	59.5	0.34
G20－113－1	Parallel(3.4 m－top)	88.3	58.2	0.27
G20－113－2	Parallel(3.4 m－end)	121.5	59.6	0.33
G21－113－1	Parallel(6.0 m－top)	124.1	62.1	0.30
G21－113－2	Parallel(6.0 m－end)	91.3	63.3	0.27
G22－113－1	Parallel(7.9 m－top)	155.3	66.3	0.30
G22－113－2	Parallel(7.9 m－end)	134.2	66.0	0.30
Average：parallel	Average according to direction	127.3	62.6	0.30
Average：perpendicular		135.4	57.9	0.33
Average：top	Average according to distance to the deposition hole wall	134.5	61.7	0.31
Average：end		120.1	58.8	0.32

According to samples′ directions and distances，the 12 samples can be divided into 4 groups. Table 4 shows the parameter averages for each group.

It can be found from Tables 2 to 4 that：

(1) In terms of UCS，as presented in Tables 2 and 4，both individually(except core borehole G20) and averagely，the samples collected in the direction perpendicular to the maximum principal stress are slightly stronger than samples in the parallel direction；and samples from the top of the core boreholes(nearest to the deposition hole wall) have slightly higher strength than those from the end of the core boreholes(about 1.5 m away from the deposition hole wall). Therefore，it seems that the rock in the inner part that experienced higher temperature during heating stage，and the rock in the direction perpendicular to maximum principal stress that were maximum loading during excavation and heating stage，are both stronger.

Table 3　Summary of crack stresses(σ_{ci} and σ_{cd}) and maximum volumetric strains(ε_{vmax} and ε_{vcmax})

Sample number	Crack stress from ε_{vc}-σ curves/MPa		Crack stress from AE/MPa		ε_{vcmax} (ε_{vc} at σ_{ci})	ε_{vmax} (ε_{v} at σ_{cd})
	σ_{ci}	σ_{cd}	σ_{ci}	σ_{cd}		
G17－113－1	60.0	100.0	75.0	120.0	0.000 249	0.000 720
G17－113－2	55.0	85.0	70.0	108.0	0.000 345	0.000 850
G18－113－1	70.0	115.0	75.0	140.0	0.000 255	0.000 780
G18－113－2	60.0	90.0	60.0	115.0	0.000 294	0.000 670
G19－113－1	85.0	140.0	80.0	165.0	0.000 271	0.000 960
G19－113－2	78.0	115.0	75.0	145.0	0.000 330	0.000 870
G20－113－1	45.0	85.0	75.0	85.0	0.000 189	0.000 750
G20－113－2	65.0	100.0	80.0	120.0	0.000 279	0.000 750
G21－113－1	60.0	110.0	80.0	120.0	0.000 216	0.000 800
G21－113－2	45.0	70.0	65.0	70.0	0.000 119	0.000 610
G22－113－1	78.0	135.0	80.0－90.0	140.0	0.000 243	0.000 920
G22－113－2	71.0	120.0	80.0	130.0	0.000 161	0.000 800
Average：parallel	60.7	103.3	77.5	110.8	0.000 201	0.000 772
Average：perpendicular	66.0	107.5	72.5	132.2	0.000 291	0.000 808
Average：top	66.3	114.2	78.3	128.3	0.000 237	0.000 882
Average：end	62.3	96.7	71.7	114.7	0.000 255	0.000 758

Table 4　Parameter averages for each group

Name	*UCS*/MPa	Young′s modulus /GPa	σ_{ci}/MPa (from ε_{vc} curve)	σ_{ci}/MPa (from AE)	σ_{cd}/MPa (from ε_{v}-σ curve)	σ_{cd}/MPa (from AE)	ε_{vcmax}	ε_{vmax}
Perpendicular-top	146.4	61.2	71.7	76.7	143.0	141.7	0.000 258	0.000 82
Parallel-top	122.6	62.2	61.0	80.0	110.0	115.0	0.000 216	0.000 82
Perpendicular-end	124.4	54.6	64.3	78.0	96.6	122.7	0.000 323	0.000 79
Parallel-end	115.7	63.0	60.3	75.0	96.5	106.7	0.000 186	0.000 72

(2) In terms of Young′s modulus，when compared according to the sampled direction as presented in Tables 2 and 4，the tendency is that samples taken near the deposition hole wall at the same depth have almost the same value；but for samples taken about 1.5 m away from the deposition hole wall，the samples collected in the direction perpendicular to the maximum principal stress have lower values than those from the parallel direction. If compared according to the samples′ distance to the deposition hole，as shown in Tables 2 and 4，in the direction perpendicular to the maximum principal stress，samples near the deposition hole wall have higher values of Young′s modulus than those about 1.5 m away；however，in the direction parallel to the maximum principal stress，samples at the same depth have approximately same value.

(3) As presented in Tables 3 and 4，from ε_{vc}-σ curves results，both individually(except core borehole G20) and averagely，the samples(except those from borehole G20) from the direction perpendicular to the maximum principal stress have slightly higher cracking stress(crack initiation stress σ_{ci} and crack damage stress σ_{cd}) than those from the parallel direction. AE has the same result for crack damage stress σ_{cd} but an opposite result for crack initiation stress σ_{ci}. Indicated by ε_{vc}-σ curves(except borehole G20) and AE results as shown in Tables 3 and 4，the samples collected from the top of the core boreholes exhibit slightly higher cracking stresses(crack initiation stress σ_{ci} and crack damage stress σ_{cd}) than those from the end.

(4) As can be seen from Tables 3 and 4，at the same depth，the samples from the direction perpendicular to maximum principal stress unanimously have slightly higher maximum crack volumetric strains(ε_{vcmax}) than those from the parallel direction. Compared according to the distance to the deposition hole wall as shown in Tables 3 and 4，the situation is more complicated. In the direction perpendicular to major principal stress and borehole G20，within a borehole，the samples collected near the deposition hole wall have lower maximum crack volumetric strains(ε_{vcmax}). Averagely，the samples collected near the deposition hole wall have lower maximum crack volumetric strains (ε_{vcmax})，but they have higher maximum total volumetric strains(ε_{vmax}) than those from the ends of the core boreholes.

4.5 Damage analysis

The results from UCS tests，including UCS and Young′s modulus，crack initiation stress(σ_{ci}) and crack damage stress(σ_{cd})，maximum crack volumetric strain (ε_{vcmax}) and maximum volumetric strain(ε_{vmax})，have been complied and compared respectively.

Theoretically，under an anisotropic geostress，the maximum and minimum stresses due to a circular excavation occur at the surface in the directions perpendicular to and parallel to the major principal stress respectively[15]. The thermal stress decreases with the radial distance. Thus，for the CRT，the rock near the deposition hole wall in the direction perpendicular to major principal stress should have experienced maximum load due to excavation and heating.

The occurrence of damage could be judged either by comparing the rock mechanical property changes of the same location due to excavation and heating or by comparing the property difference of rock samples from different locations after excavation and heating，especially from the maximum and minimum loaded parts. The mechanical properties of the rock in CRT before excavation and heating have not been tested yet. The latter method is herein adopted，i. e. damage is judged from the comparison of mechanical properties between samples from the directions perpendicular to and parallel to the major principal stress and between samples from the top and end of the core boreholes.

By comparing testing results of the samples from different directions(at the same depth or averagely)，it can be found that the UCS，crack initiation stresses (determined from ε_{vc}-σ curves) and crack damage stress in the direction perpendicular to the maximum principal stress are higher than those in the direction parallel to the maximum principal stress. By comparing testing results of samples from different distances to the deposition hole wall(with a borehole or averagely), it has been found that, except in borehole G20, the UCS crack initiation stress and crack damage stress at the top of the core boreholes are higher than those at the end part. From the above- mentioned comparisons, there is no evidence of damage by UCS, σ_{ci} (from ε_{vc} - σ curves) and σ_{cd}. Therefore, it can be inferred that the surrounding rock of the CRT deposition hole has no obvious damage.

Young′s modulus has no directional difference for samples taken near the deposition hole wall, and has no obvious difference among samples from different distances to the deposition wall in the direction parallel to the maximum principal stress. Judged from Young′s modulus, it can be inferred that the surrounding rock of the CRT deposition hole has no obvious damage. It should be noted that samples from the end of core boreholes in the direction perpendicular to the major principal stress have apparently lower Young′s moduli than those of other samples, which might be due to geological factor.

Analysis of the maximum volumetric strain indicated that samples from the direction perpendicular to the maximum principal stress unanimously show slightly higher maximum crack volumetric strain (ε_{vcmax}) than those with the same depth and nearly the same distance to the deposition wall from the parallel direction. For the 6 samples collected near the deposition hole wall, noting that the 6 samples have almost the same Young′s modulus and the 3 samples from the direction perpendicular to the maximum principal stress have higher UCS, σ_{ci} and σ_{cd} (determined from ε_v - σ curve) than the other three from the parallel direction, it seems reasonable to attribute this slightly higher value of the maximum crack volumetric strain to some microfractures in the corresponding rock due to excavation and heating during the CRT. But the micro-fracturing occurred only to a small extent, if it did exist. In the direction perpendicular to the maximum principal stress, the samples collected about 1.5 m from the deposition hole wall have higher crack volumetric strain than those from the top part. This is reasonably attributed to their lower Young′s moduli due to possibly geological cause. The possible damage in the form of micro-fracture due to excavation and heating might be seemingly masked.

In summary, judged from UCS, Young′s modulus, σ_{ci} and σ_{cd}, the surrounding rock of the CRT deposition hole have not been damaged during the CRT. Crack volumetric strain data show that microfracturing might have occurred, but only to a small extent.

5　CONCLUSION

To investigate the possible damage to the surrounding rocks arising from the excavation and heating in CRT, uniaxial compression tests with the MTS 815 Rock Mechanics Testing System(MTS 815) were performed on 12 core samples collected from 6 sub-horizontal core boreholes drilled in the directions perpendicular and parallel to the major principal stress at three depths in the deposition hole DD0092G01. Uniaxial compression strength, Young′s modulus, crack initiation stress and crack damage stress (determined from volumetric strain-axial stress curve or from acoustic emission), maximum total and crack volumetric strains(determined from volumetric strain-axial stress curve) have been determined. Parametric comparisons were made between samples from the direction perpendicular(with maximum load) and from the direction parallel(with minimum load) to the maximum principal stress and between samples from the top(higher thermal stress) and from the end(lower thermal stress) of the sub-horizontal core boreholes. Judged from relatively higher values of the maximum crack volumetric strains, damage of small extent in the form of microfracturing probably occurred in the rock near the deposition hole wall in the direction perpendicular to the maximum principal stress after excavation of the deposition hole and during the later heating stage. There is no evidence of any damage by UCS, Young′s modulus, crack initiation stress(from volumetric strain-axial stress curve) and crack damage stress(determined from volumetric strain-axial stress curve or from acoustic emission)，maximum total volumetric strains.

The comparisons in this study for UCS testing were conducted among samples taken from different locations after heating and not among samples of the same location taken prior to and after heating. The inherent spatial geological difference might have masked the damage to some extent.

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